### Title

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# Thermal diffusivity of municipal solid waste based on inverse analysis of in-situ heat extraction test

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## ABSTRACT

In this study, a two-dimensional finite difference model was used to simulate the heat transfer occurred during a 17-day heat extraction test performed in an MSW landfill cell in Santee, California. The heat was extracted using serpentine heat exchangers installed 6 m above the base liner of the cell, and started after the waste reached a stable temperature value of 52 °C. The model used was based on the differential heat conduction equation and an inverse analysis was performed to estimate the thermal diffusivity of the waste. The values of in-situ thermal diffusivity obtained ranged from $7.85\times10^{-7}$ m$^2$/s to $1.05\times10^{-6}$ m$^2$/s and are consistent with the higher range of values presented in the literature for MSW.

**Keywords:** municipal solid waste, landfill, thermal response test, heat extraction, inverse analysis, thermal diffusivity

## 1 INTRODUCTION

It is well known that heat is generated as a byproduct of the biological decomposition of the organic matter present in municipal solid waste (MSW) and it has been observed to lead to an increase in temperature in MSW landfills, with values greater than 50 °C being sustained for several decades (Rees, 1980; Bookter and Ham, 1982; Young, 1992; Kjeldsen et al., 2003; Yeşiller et al., 2005). This heat is an alternative energy resource with potential to be extracted and used either directly, for heating nearby facilities (Emmi et al. 2016), or to regulate waste temperatures and optimize processes within the landfill, as methane generation and waste settlements, in addition to reducing the temperature gradient across the landfill base liner and consequently preventing damages to the clay liner and geomembrane (Farquar and Rovers, 1973; Rees, 1980; Lamothe and Edgers, 1994; Southen and Rowe, 2005; Bareither et al., 2012; Coccia et al., 2013; Jafari et al., 2014).

To properly design heat extraction systems and extract heat from landfills in a controlled manner, it is fundamental to know the thermal properties of the MSW. While several studies have determined the thermal properties of waste in the laboratory (Hanson et al., 2000 and 2008; Faitli et al., 2015; Yeşiller et al., 2015), the scale and variability in MSW are issues that add emphasis to the need for in-situ estimates of thermal properties to confirm these laboratory measurements.

This paper presents the results of a 17-day heat extraction thermal response test using horizontal heat exchangers installed in an MSW landfill in Santee, California. The geometry of the system was reproduced in a two-dimensional finite difference analysis, which compared the field and the modelled results to estimate the in-situ thermal diffusivity of the heat extraction system.

## 2 FIELD EXPERIMENT

### 2.1 Layout of heat extraction system

A horizontal heat extraction system was installed in a new cell of an MSW landfill in Santee, California. The weather in the region is warm and dry, with an average maximum temperature of 25.9 °C and minimum of 11.8 °C, and average annual precipitation of 224 mm. The system was installed between August and October of 2016, which coincides with the dry season of the region, with only 2.5 mm of precipitation being registered during the construction period. The composition of the MSW placed at the new cell was not analyzed for this study, but it was assumed to be representative of the overall disposed waste reported by the City of San Diego (2014). After placement, the waste was compacted to reach an average total unit weight of 8.7 kN/m$^3$.

The heat extraction system consisted in circulating cold water through pipes embedded in a waste cell in which temperatures had naturally reached values greater than the ambient ground temperature due to the biodegradation of the organic matter. The horizontal geothermal heat exchanger (GHE) pipe was placed with a serpentine configuration, 6 m above the base liner of the cell, as presented in Figure 1(a). The vertical spacing of 6 m corresponds to one lift of waste, so the system was installed between the placement of two consecutive lifts, minimizing the interference with landfill operations. Four lifts of waste of 6 m each were placed on top of the heat exchangers used in this study, with a total of 30 m of waste in the cell. The heat exchanger used were high density polyethylene (HDPE) pipes with internal diameter of 25 mm.

### 2.2 Instrumentation and monitoring

Four thermistor strings (Model 3810 from Geokon, Inc. of Lebanon, NH), each containing three thermistors at different locations along a single 45 m-cable, were used for temperature monitoring during this experiment. The thermistors were installed horizontally, with the spacing between each thermistor along the string of approximately 15 m, with the first one positioned 16.8 m from the waste slope, as shown in Figure 1(a).

The thermistor strings were positioned in a way to provide a horizontal profile of temperatures as a function of time and distance from the pipes. The first thermistor string, referred to as String A, was placed 2 m away from the outermost segment of the heat exchanger pipe. String B was placed 1 m from the outermost heat exchanger segment, String C was attached to the outermost heat exchanger segment and String D was placed between the first two segments of the serpentine heat exchanger (1 m from each). One additional thermistor was installed in the data logger, outside the waste cell, to measure the air temperature during the experiment. Additionally, two pipe plug thermistors (model TH44004 from Omega Engineering) were connected to the entrance and exit of the heat exchanger to measure the temperature of the water entering and exiting the system, and a flowmeter (model SM7601 from IFM Electronic gmbh) was connected to the pipe. The serpentine configuration of the heat exchanger, as the position of the sensors, is showed in Figure 1(b). The water tank, chiller and generator used to circulate water during the heat extraction are also showed in Figure 1(b).

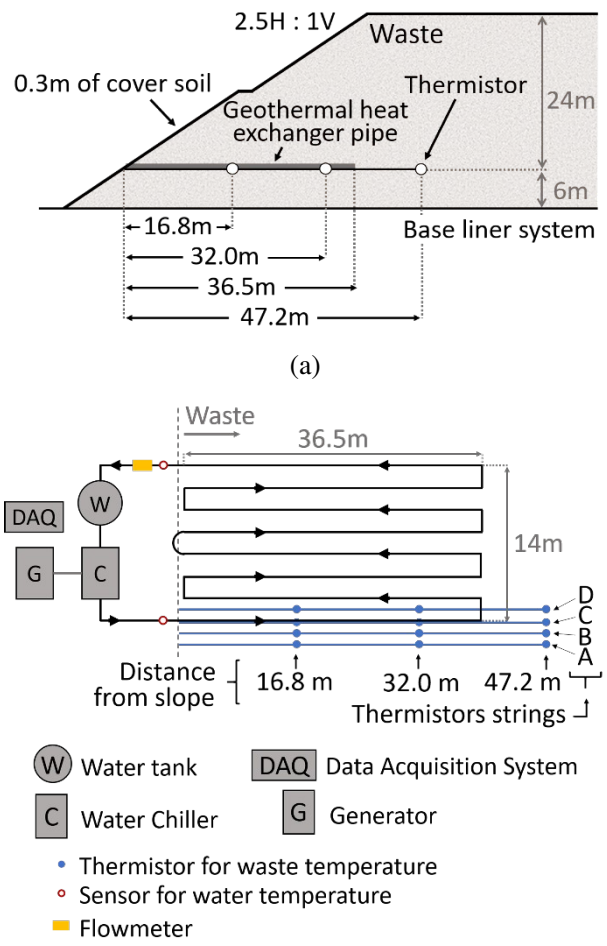



Fig. 1. Design of heat extraction system: (a) Cross-sectional elevation view parallel to the GHE pipes; (b) Serpentine configuration of the geothermal heat exchanger pipes showing locations of the thermistor strings.

The MSW temperature was monitored for 13 months, since the placement of the waste until reaching stabilized values, at approximately 52 °C. After that, a thermal response test (TRT) was performed using an approach consistent with that proposed by Mogensen (1983). Heat was extracted from the waste through the circulation of cold water within the GHE pipes for 405 hours (approximately 17 days) without interruption. The volumetric flow rate was kept nearly constant and equal to $2.1\times10^{-4}$ $m^3/s$ (0.21 L/s), maintaining a turbulent flow for the duration of the test (Reynold's number of 13191) and resulting on an estimate average heat transfer rate of 11.8 kW.

This thermal response test, with its results, was described in detail by Nocko et al. (2020), who used the temperature variation results to estimate the thermal conductivity of the MSW using an analytical approach.

The variation of the waste temperature during the heat extraction is showed in Figures 2(a) and 2(b) for sensors at 16.8 m and 32.0 m from the waste slope,

respectively. There was no variation in temperature for the sensors placed at 47.2 m.

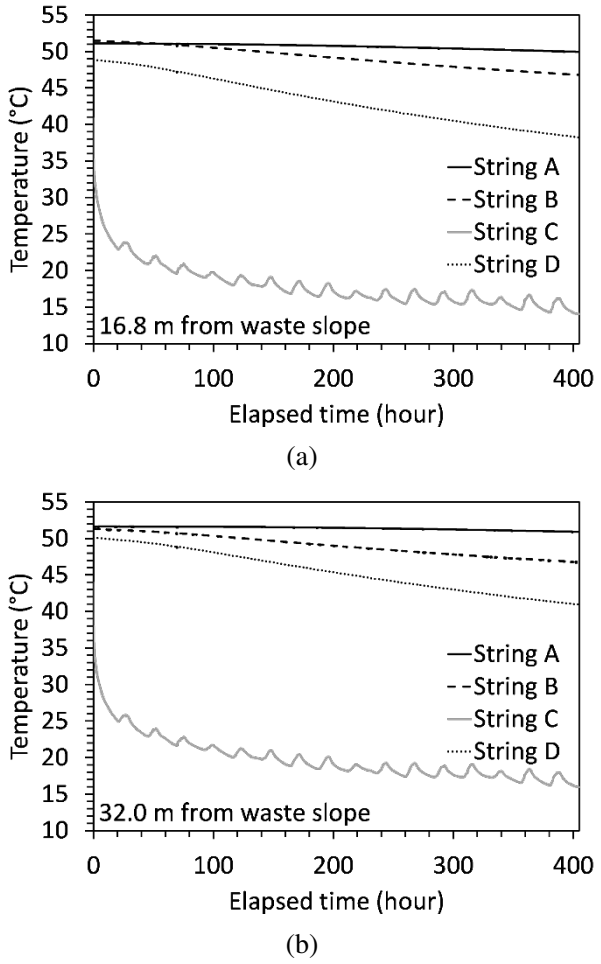



Fig. 2. Waste temperature evolution during heat extraction TRT: (a) at 16.8 m from waste slope; (b) at 32.0 m from waste slope.

In Figure 2(a) and 2(b), a sharp decrease in temperatures is observed for sensors at String C, which was attached to the heat exchanger. Strings B and D also presented a decrease in temperatures, but the difference is more pronounced for String D, since it was equally influenced by two segments of GHE, instead of just one, as String B. Temperatures at String A, 2 m from the heat exchanger, presented a more subtle decrease of 1.0 °C.

## 3 TWO-DIMENSIONAL FINITE DIFFERENCE ANALYSIS

To estimate the in-situ thermal diffusivity $\alpha$ of MSW, a simplified inverse analysis was performed using a 2D finite difference implementation of the differential heat conduction equation, defined as:

$$\frac{\partial T}{\partial t}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right) \quad (1)$$

where x and y are spatial variables. Specifically, the 405 hours of heat extraction were simulated, and the results were compared to the temperature measured data. The thermal diffusivity was varied until the best fit between field and modeled data was obtained. The finite difference explicit method used to calculate the temperature $T_{i,j}^{k+1}$ at position ($x_i$,$y_j$) and time $t_{k+1}$ was implemented with a forward difference for the time derivative and a second-order central difference for the space derivative (FTCS), as follows:

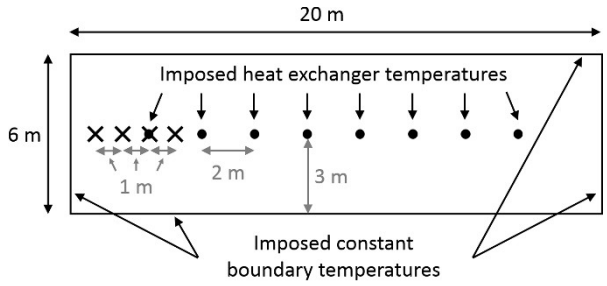
$$T_{i,j}^{k+1}=T_{i,j}^{k}+\Delta t \times \alpha\left(\frac{T_{i+1,j}^{k}+T_{i-1,j}^{k}-4\times T_{i,j}^{k}+T_{i,j+1}^{k}+T_{i,j-1}^{k}}{h^2}\right) \quad (2)$$

where $\Delta t$ is the time increment and $h$ is the space increment, for a mesh with $\Delta x=\Delta y=h$. For this study, $\Delta t$ = 10 s and $h$ = 0.01 m. The stability of the method was verified by applying the von Neumann condition for a 2D problem:

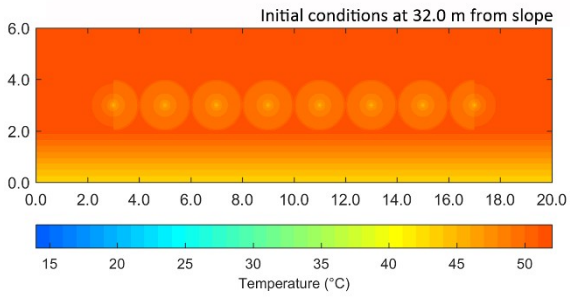
$$\alpha\times\left(\frac{\Delta t}{h^2}\right)\leq\frac{1}{4} \quad (3)$$

The experimental data used in this analysis were obtained from sensors positioned at distances of 16.8 m and 32.0 m from the slope face. It was assumed that heat transfer occurs only due to conduction, neglecting the effects of convection and possible effects of heat generation within the waste. In other words, it is assumed that the time scale for anerobic heat generation is longer than the period of the heat extraction TRT.

The geometry simulated is presented in Figure 3(a) and it corresponds to the same geometry of the system installed in the field. The boundaries of the simulated region were fixed at 3 m from the outermost GHE segments. The initial temperatures used in this analysis are shown in Figure 3(b) and were assumed to vary as a function of the radial distance from the GHE segments. For the bottom 2 m of the simulated area, the temperature was assumed to decrease linearly with depth, being described by a function that varies from 51.5 °C at 1 m below the system, to 30.1 °C, at 6 m below the system, directly above the base liner of the cell. The temperature monitoring data was reported by Nocko et al. (2020). At the borders of the simulated area, the initial temperature was also imposed as a constant boundary condition during the simulation.



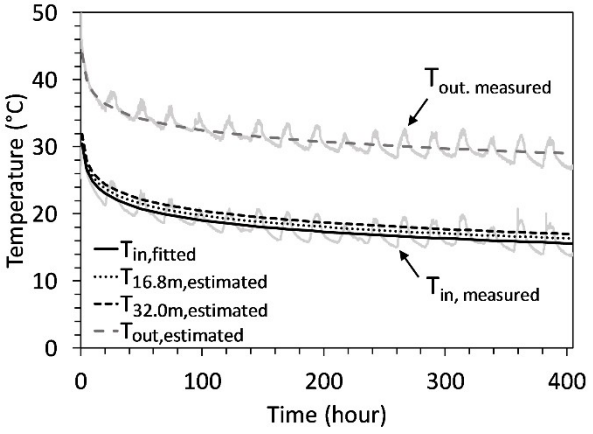

(a)



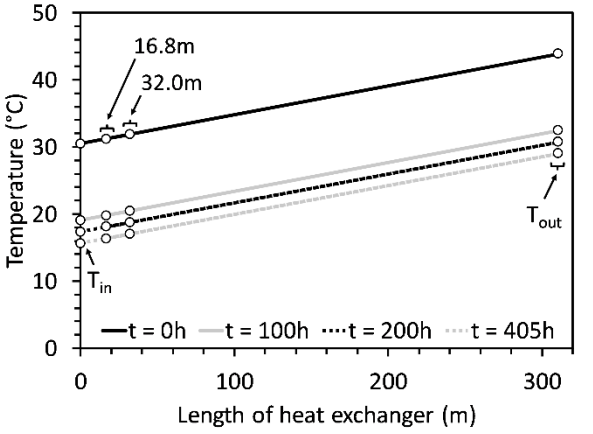

(b)

Fig. 3. Finite difference analysis of the heat conduction equation: (a) Vertical cross-section geometry of area simulated showing boundary conditions; (b) Initial 2D distribution in temperatures at 32.0 m from cell slope.

A time-dependent temperature boundary condition was applied to the location of each of the GHE segments in the 2D geometry, using the measured entering ($T_{in}$) and exiting ($T_{out}$) fluid temperatures to define this boundary condition, as shown in Figure 4Error: Reference source not found(a). A decreasing logarithmic relationship was fit to the average entering fluid temperature time history. The exiting fluid temperature was obtained by adding the average temperature difference (13 °C) to the entering temperature at each time step. It was assumed that the temperature of the heat exchanger increases linearly with distance along the serpentine heat exchanger. Accordingly, the temperature gain in each point of the serpentine heat exchanger is proportional to the length of pipe travelled by the fluid to get to that point. Time series of the temperatures imposed to points at 16.8 and 32.0 m from the cell edge are shown in Figure 4(a), and the temperatures along the length of the heat exchanger for different times are presented in Figure 4(b). Simulations run by Philippe et al. (2011) show a linear variation in fluid temperature for times larger than the residence time. In this study, the fluid residence time within the geothermal heat exchanger of Layer 2 is approximately 12 minutes, which is significantly small compared to the simulated time of 405 hours, supporting this simplified assumption of a linear variation in temperature along the length of the heat exchanger.




(a)




(b)

Fig. 4. Finite difference analysis of the heat conduction equation: (a) Time series of imposed heat exchanger temperatures at different locations; (b) Spatial distribution in imposed heat exchanger temperatures for different times.

Several simulations were run varying the value of $\alpha$, and the results obtained were compared with field data to define the coefficient of determination, $R^2$, obtained in each simulation. The trends in $R^2$ and $\alpha$ for the data at two distances from the slope face are shown in 5. The values of $\alpha$ resulting in the highest $R^2$ were $1.05\times10^{-6}$ $m^2/s$ at 16.8 m from the slope face, and $7.85\times10^{-7}$ $m^2/s$ at 32.0 m from the slope face, resulting in an average $\alpha$ of $9.2\times10^{-7}$ $m^2/s$. Comparison between the field measurements and the horizontal profiles of temperatures obtained with the best fitted $\alpha$ for the end of the TRT are shown in Figures 6(a) and 6(b) for sensors at 16.8 m and 32.0 m from the cell edge, respectively. Two main reasons can explain the difference in $\alpha$ obtained for the two distances from the slope face. The first, which is a common challenge when dealing with MSW, is the heterogeneity of the material. Depending on the type of waste placed around one set of sensors, its thermal, mechanical and

hydrological properties might present variations when compared to other regions of the cell. The second reason for difference in the results is more practical and relates the accuracy of the sensors and possibility of wrong measurements, which affects the fitting process.

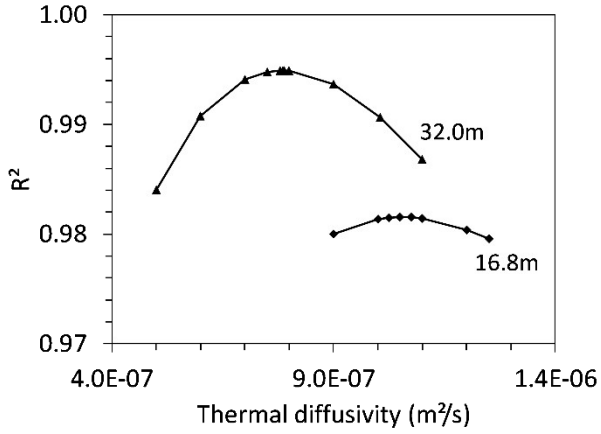



Fig. 5. Coefficient of determination obtained from inverse analysis with different values of thermal diffusivity for waste at 16.8 m and 32.0 m from the slope face.

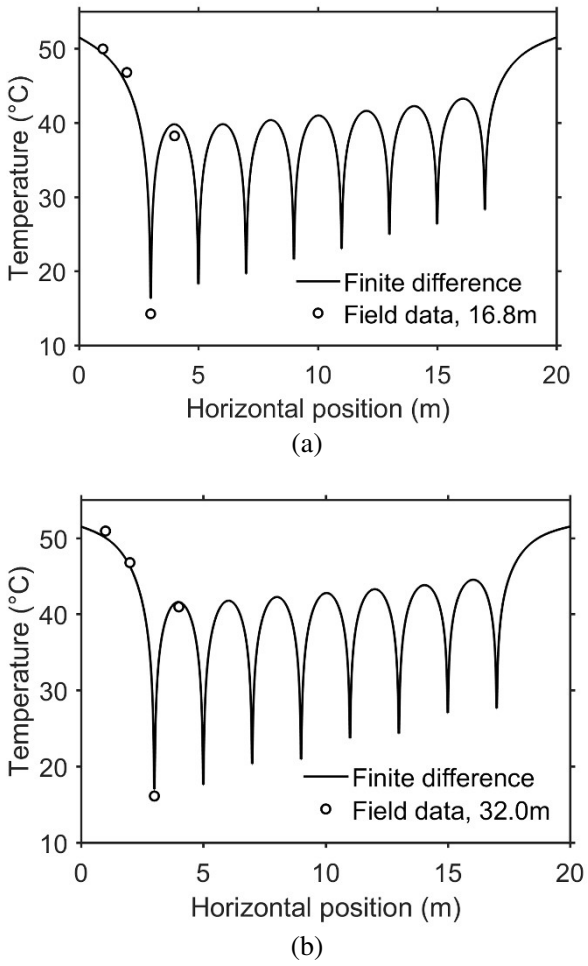



Fig. 6. Finite difference analysis results: temperature profile obtained at the end of the heat extraction period for sensors at (a) 16.8 m and (b) 32.0 m.

The 2D profile of temperatures obtained at the end of the heat extraction period at 32.0 m is presented in Figure 7, and the influence from the different fluid temperatures along the pipe can be observed. Since the cold water enters the waste cell through the GHE segment at the left, the waste around that segment is slightly colder than in other regions. As the water flows through the pipe, the fluid temperature increases as it absorbs heat from the MSW. This reduces the temperature gradient between the waste and the fluid, and consequently the amount of heat extracted. In this manner, the waste around GHE segments further from the fluid entry is not so strongly affected, as shown in Figure 7.

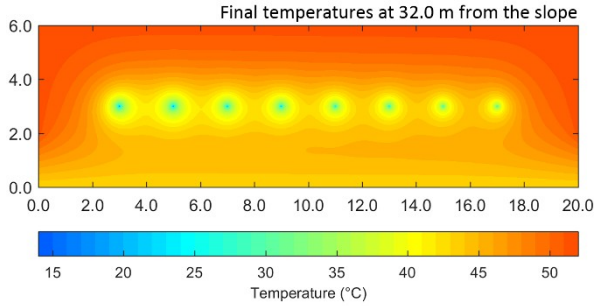



Fig. 7. Finite difference analysis results: 2D temperature profile at 32.0 m from cell slope after 405 h of heat extraction.

## 4 CONCLUSIONS

In this study, the in-situ thermal diffusivity of MSW was estimated using a simplified inverse analysis of a 17-day heat extraction test performed on a horizontal heat exchanger installed in a MSW landfill. The field experiment was carried out only after the MSW temperatures were stabilized, and the inverse analysis was based on a two-dimensional finite difference simulation of the heat extraction. The estimated values of in-situ thermal diffusivity ranged from $7.85\times10^{-7}$ to $10.5\times10^{-7}$ m$^2$/s. These values are consistent with the range presented in literature for laboratory tests but are more in line with the upper bound of values, indicating the relevance of determining these variables in-situ.

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